Plasma Instabilities in Post-Eruption Solar Corona, Formation of Plasmoids and Supra-Arcade Downflows

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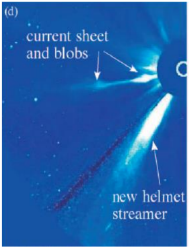

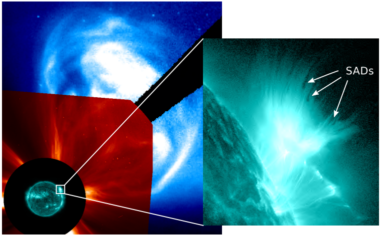

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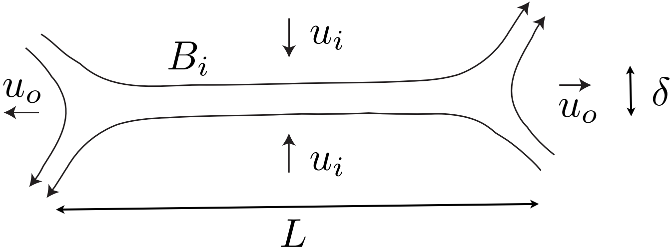
- Davina Innes, Sibylle Günter, Qingquan Yu, Karl Lackner

Outline

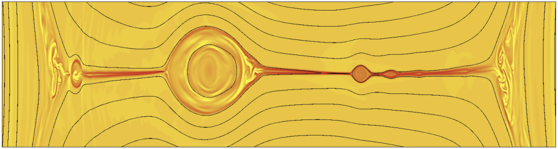
- 2D plasmoid instability
  - Linear theory
  - Scaling laws & reconnection rate in nonlinear regime
  - Distribution of Plasmoids
  - Hall MHD and reconnection phase diagram
- Plasmoid instability in 3D
  - Linear oblique plasmoid instability in 3D geometry with a guide field
  - Nonlinear simulation
  - Reconnection rate – comparison with 2D
  - Energy spectrum and characteristic of turbulence
- Supra-arcade downflows (SADs)
  - Observation & Interpretations
  - Ralyleigh-Taylor type instabilities in the reconnection exhaust region
- Future directions & possible connection with laboratory plasma physics

Classical Sweet-Parker Theory



- $S = LV_A/\eta$
- $\delta \sim L/\sqrt{S}$, $u_o \sim V_A$,$u_i \sim V_A/\sqrt{S}$
- Solar Corona: $S \sim 10^{12}$, $\tau_A = L/V_A \sim 1s \Rightarrow \tau_{SP} \sim 10^6 s \gg$ Solar flare time scales $10^2 - 10^3 s$.

Plasmoid Instability Leads to Reconsideration of Fast Reconnection in Resistive MHD



- The Sweet-Parker current sheet is unstable to secondary tearing instability at high S.
- Linear theory predicts $\gamma \sim S^{1/4} V_A / L$ and the number of plasmoids $\sim S^{3/8}$. (Loureiro et al. 2007)
- The key point is that the equilibrium also scales with S: $\delta_{SP} \sim L S^{-1/2}$.

Linear Plasmoid Instability

Harris sheet profile $\mathbf{B} = B_o \tanh(x/a)\hat{\mathbf{y}}$

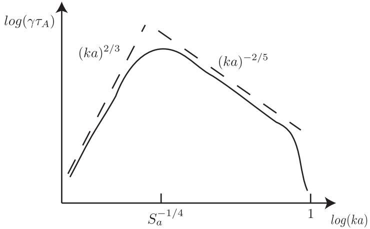
$$\gamma\tau_A \sim \begin{cases} S_a^{-3/5}(ka)^{-2/5}(1-k^2a^2)^{4/5}, & ka \gg S_a^{-1/4} \\ S_a^{-1/3}(ka)^{2/3}, & ka \ll S_a^{-1/4} \end{cases}$$

Peak $\gamma \sim S_a^{-1/2}$ at $ka \sim S_a^{-1/4}$, where $S_a = aV_A/\eta$, $\tau_A = a/V_A$.

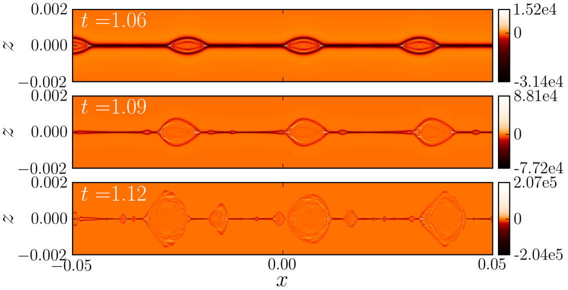
Coppi et al. 1976

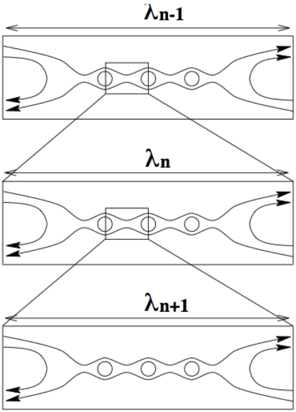
Translate to the Sweet-Parker language:
$S \equiv LV_A/\eta$, $a \to \delta_{SP} \sim LS^{-1/2}$:
The peak γ occurs at $kL \sim S^{3/8}$ with
$\gamma_{max} \sim S^{1/4}V_A/L$.

Bhattacharjee et al. 2009



Plasmoid Instability Leads to Fractal-like Cascade

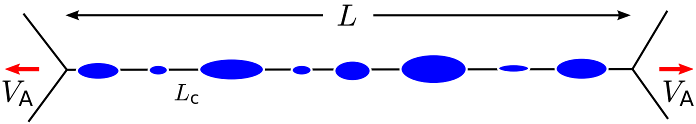




Shibata & Tanuma (2001)

Unstable when $S > S_c \sim 10^4$. The reconnection rate $\simeq 10^{-2} BV_A$, nearly independent of S. No. of plasmoids $n_p \sim S$, secondary current sheet width and length $\sim S^{-1}$, and $J \sim S$.

Heuristic Argument Based on Marginal Stability

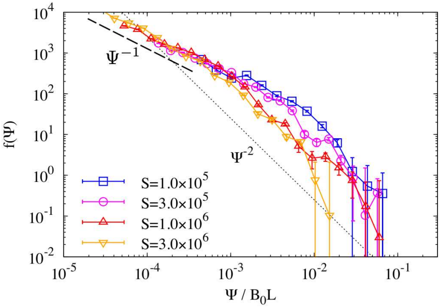


- Secondary current sheets should be close to marginally stable
  - Cascade to smaller scales stops when local current sheets become stable to the plasmoid instability
  - New plasmoids are generated when local current sheets exceed a critical length.
- $L_c \sim S_c\eta/V_A \sim LS_c/S$, $\delta_c \sim L_c/S_c^{1/2} \sim LS_c^{1/2}/S$, $J \sim B/\delta_c \sim BS/LS_c^{1/2}$
- Number of plasmoids $n_p \sim L/L_c \sim S/S_c$
- Inflow speed $\sim V_A/\sqrt{S_c}$, area transfer rate into each plasmoid $\sim L_cV_A/\sqrt{S_c}$
- Total area transfer rate $\sim n_pL_cV_A/\sqrt{S_c} \sim LV_A/\sqrt{S_c} \sim \sqrt{S/S_c}\times$S-P rate

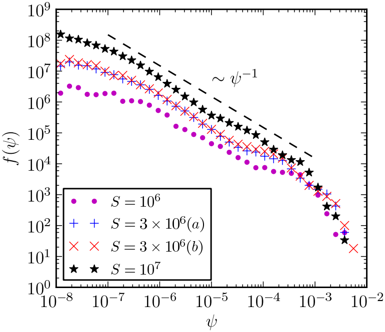
Statistical Distribution of Plasmoids

- Fermo *et al.* (2010): $f(\psi)$ decays exponentially at large ψ.
- Uzdensky et al. (2010): $f(\psi) \sim \psi^{-2}$
- Huang and Bhattacharjee (2012): $f(\psi) \sim \psi^{-1}$ followed by an exponential falloff at large ψ

Loureiro et al. PoP (2012)



Huang & Bhattacharjee PRL (2012)

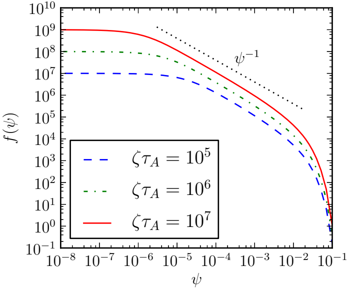


Kinetic Model of Plasmoid Distribution

$$\partial_t F + \gamma \frac{\partial F}{\partial \psi} = \zeta \delta(\psi) h(v) - \frac{FH}{\tau_A} - \frac{F}{\tau_A},$$

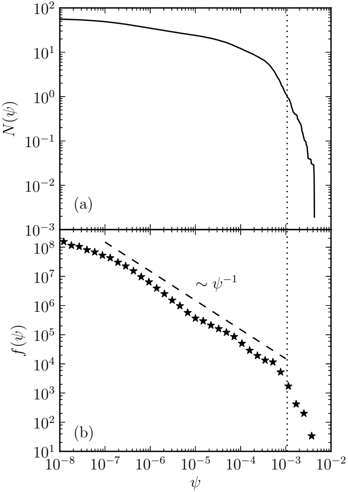
$$\text{where } H(\psi, v) = \int_{\psi}^{\infty} d\psi' \int_{-\infty}^{\infty} dv' \frac{|v - v'|}{V_A} F(\psi', v').$$

- $h(v)$ is the distribution in relative velocity when new plasmoids are generated.
- Plasmoid loss term due to merging is proportional to relative speed $|v - v'|$.
- Distribution in ψ is recovered via $f(\psi) = \int_{-\infty}^{\infty} F(\psi, v) dv$
- If $|v - v'| \to V_A$, then $f \sim \psi^{-2}$.



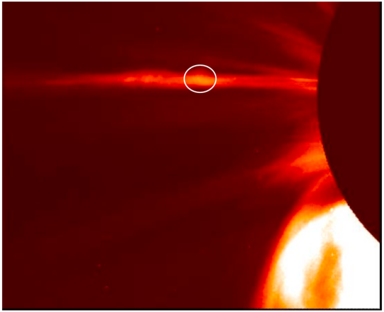
Where is Power Law Expected?

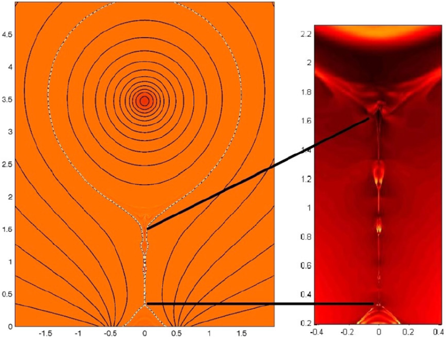
- Transition from power law to exponential occurs when the dominant loss mechanism switches from coalescence to advection — approximately when $N \sim 1$.
- Plasmoids in the power-law regime have to be deep in the hierarchy, while plasmoids in the exponential tail are the very largest plasmoids in each snapshot.



Plasmoids in Post-CME Current Sheet

- Left: Moving bright blobs in LASCO white light coronagraphy may be identified as plasmoids.
- Right: Plasmoids in the post-CME current sheet from a $S = 10^5$ simulation of the loss of equilibrium CME model

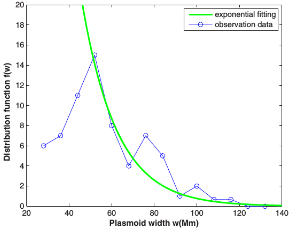




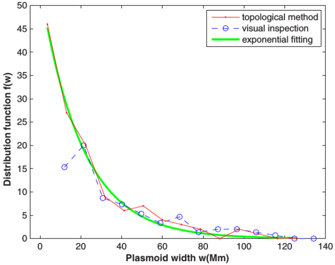
Guo et al. ApJ Lett. 2012

Plasmoid Distributions from Obs. & Expr.

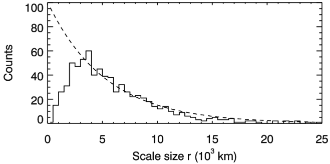
Moving blobs in post-CME current sheet (Guo et al. 2013)



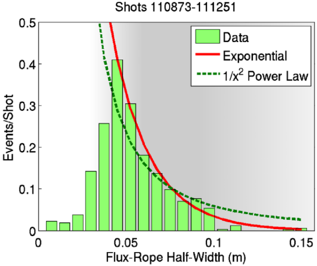
2D CME simulation



Flux transfer events (FTEs) in magnetopause (Fermo et al. 2011)



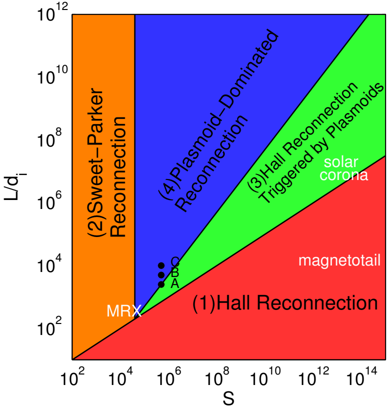
Flux ropes in MRX (Dorfman et al. 2014)



Including Hall Effect – Phase Diagram

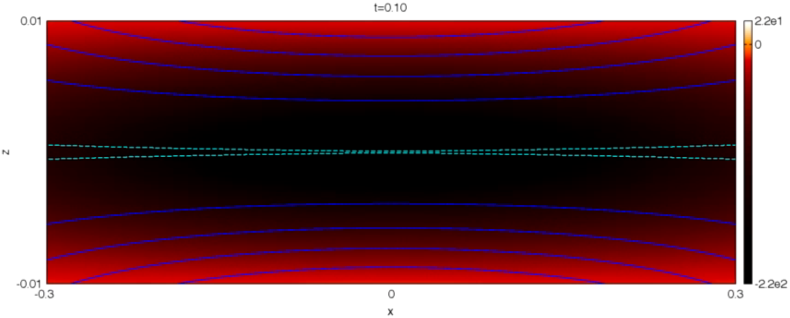
$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + d_i \frac{\mathbf{J} \times \mathbf{B} - \nabla p_e}{\rho} + \eta \mathbf{J}$$

- Another dimensionless parameter L/d_i in addition to S.



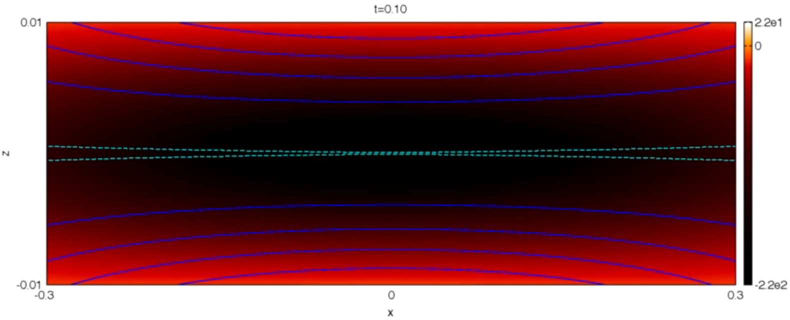
A: $S = 5 \times 10^5$, $L/d_i = 2500$
B: $S = 5 \times 10^5$, $L/d_i = 5000$
C: $S = 5 \times 10^5$, $L/d_i = 10000$

Single X-Point Hall Reconnection



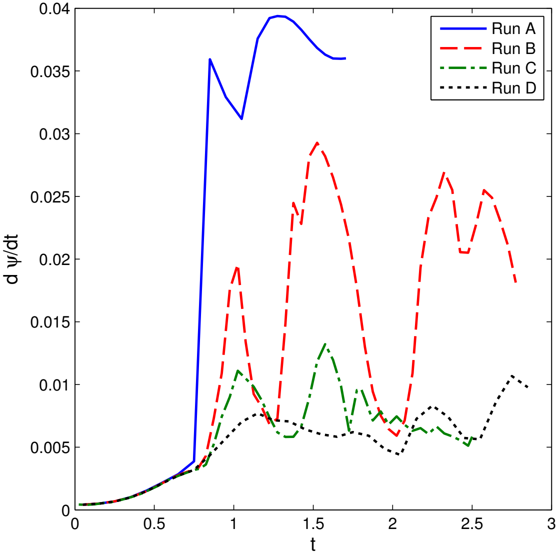
$S = 5 \times 10^5,\ L/d_i = 2500$

Intermediate Regime, Both S-P and Single X-Point Hall Solutions are Unstable



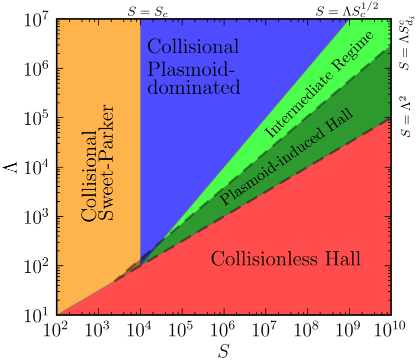
$S = 5 \times 10^5$, $L/d_i = 5000$

Reconnection Rate

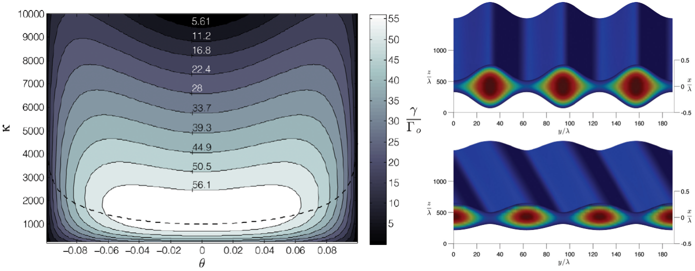


Easier to Realize Intermediate Regime in Large System

- For the same $S_{d_i} \equiv V_A d_i/\eta$, we realize the intermediate regime at $L/d_i = 5000$ but for $L/d_i \leq 2500$ a single X-point forms
- However, fully kinetic particle-in-cell simulations show continuous plasmoid formation over a much broader range in the phase diagram



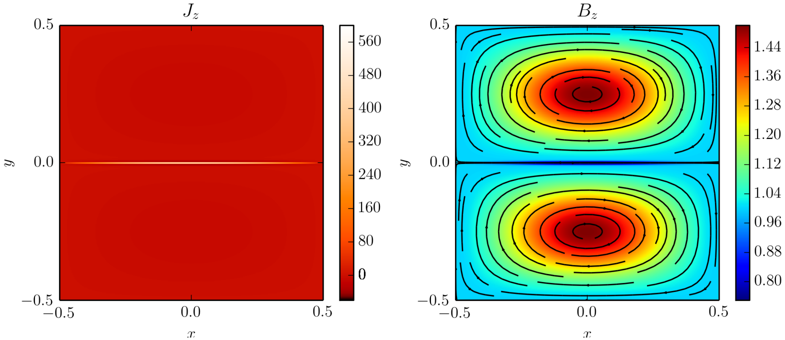
Oblique Tearing Modes in 3D



Baalrud et al. PoP (2012)

Interaction of oblique tearing modes when islands overlap $\Longrightarrow$ self-generated turbulence and stochastic field lines?

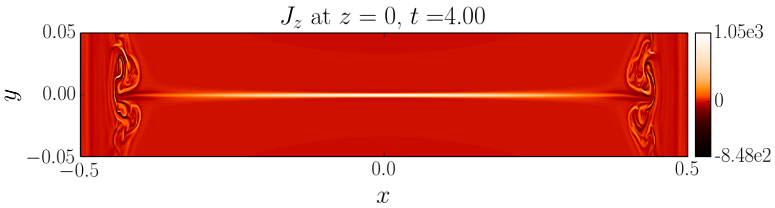
3D Simulation Setup



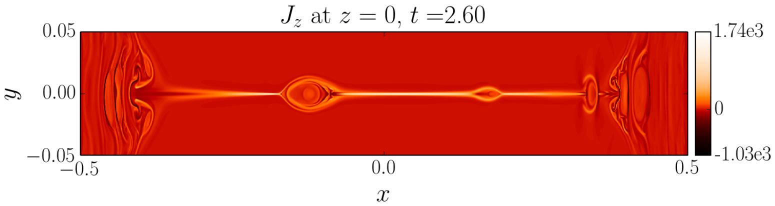
- Viscous/Resistive MHD equations.
- Initial current sheet width ~ 0.003, reconnecting $B_x \sim 1$, guide field $B_z \sim 1$.
- $\rho = 1$, $p = 2$, $\beta \equiv 2p/B^2 \sim 2$, $S = 2 \times 10^5$, $Pm = 1$.
- Simulation box $L_x = L_y = L_z = 1$; conducting walls in $x - y$ plane, periodic in z.

Sweet-Parker & 2D Plasmoid Reconnection

- **Sweet-Parker reconnection:** 2D, no initial noise

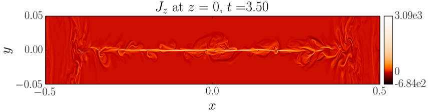


- **2D Plasmoid-Dominated reconnection:** seeded with initial random noise $\sim 10^{-3}$ on velocity

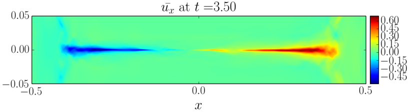


Plasmoid-Induced Turbulent Reconnection

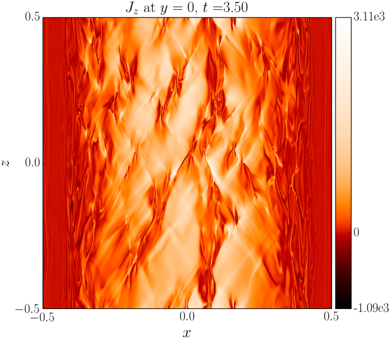
$x - y$ slice of J_z at $z = 0$



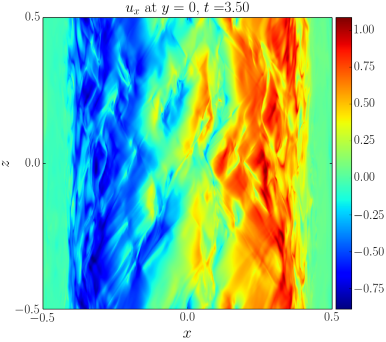
Mean field of outflow $\bar{u_x}$



$x - z$ slice of J_z at $y = 0$

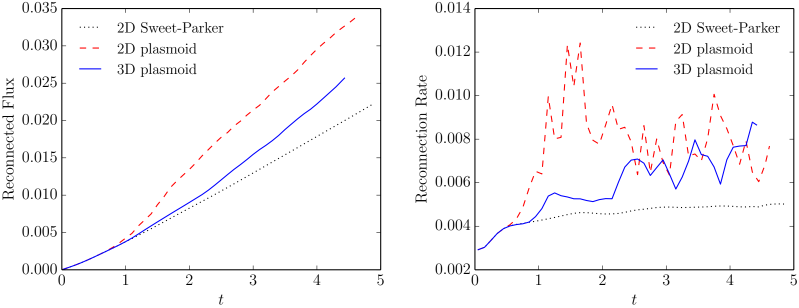


$x - z$ slice of u_x at $y = 0$

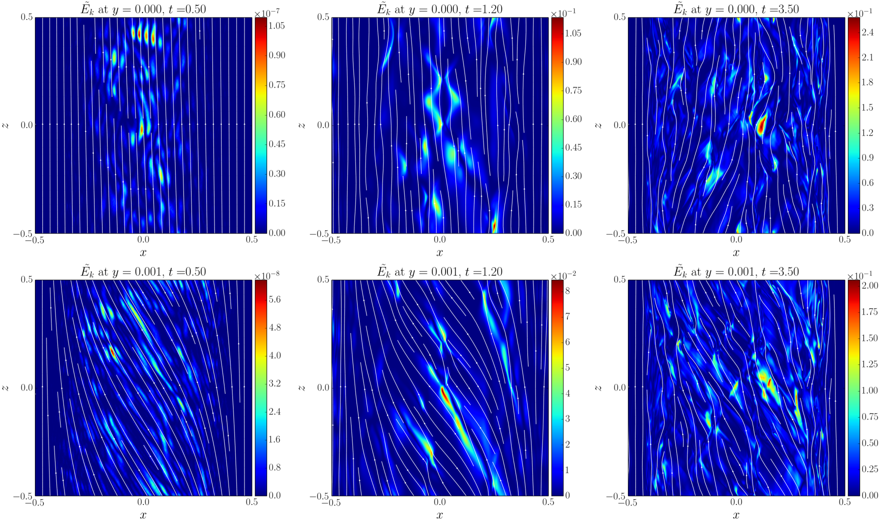


Reconnection Rate Comparison

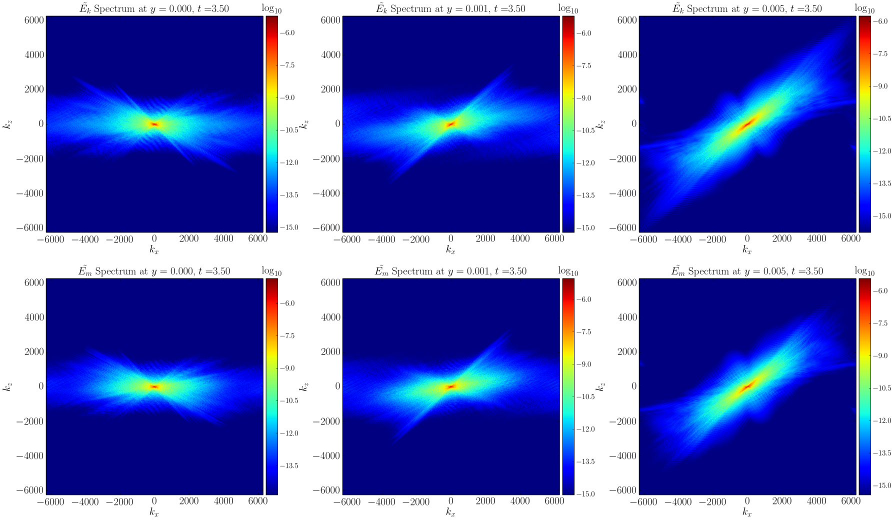
- 2D and 3D plasmoid-dominated reconnection achieve comparable, faster than Sweet-Parker, reconnection rate
- 3D reconnection is measured with the mean field $\bar{\mathbf{B}} \equiv \frac{1}{L_z} \int \mathbf{B} dz$.



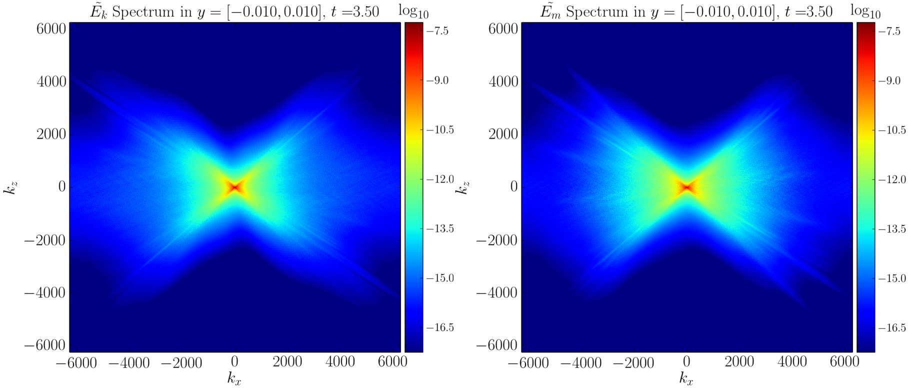
Kinetic Energy Fluctuation $\tilde{E}_k = \frac{1}{2}\left|\widetilde{\sqrt{\rho}\mathbf{u}}\right|^2$



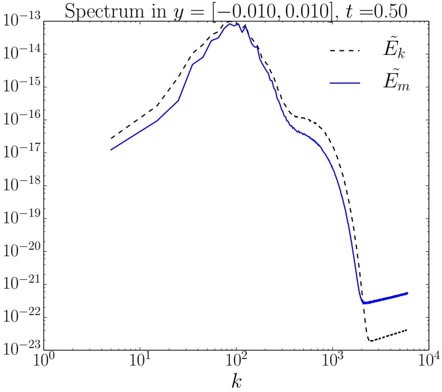
Spectrum of Energy Fluctuation

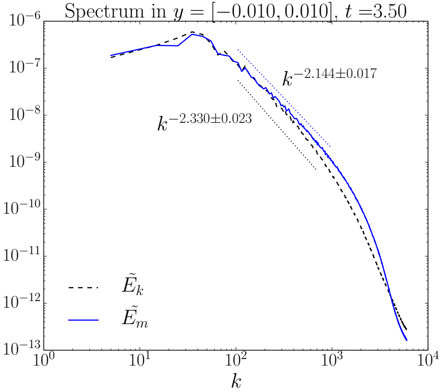


Spectrum of Energy Fluctuation, Averaged over $y = [-0.01, 0.01]$



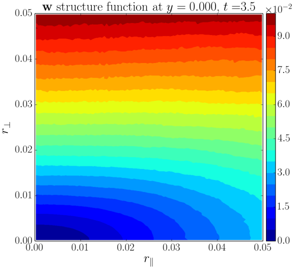
Energy Spectra Cascade

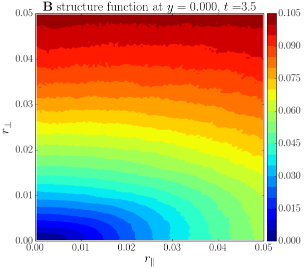


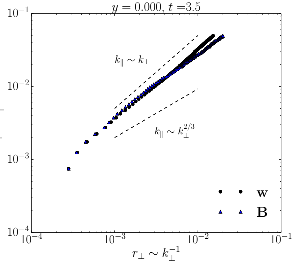


Probing Anisotropy with Structure Functions

- $\mathbf{w} \equiv \sqrt{\rho}\mathbf{u}$
- Local in plane field $\mathbf{B}_l \equiv (\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{z}}\hat{\mathbf{z}}) \cdot (\mathbf{B}(\mathbf{r}_1) + \mathbf{B}(\mathbf{r}_2))/2$
- $r_\parallel = \left|(\mathbf{r}_1 - \mathbf{r}_2) \cdot \hat{\mathbf{b}}_l\right|$, $r_\perp = \left|(\mathbf{r}_1 - \mathbf{r}_2) \times \hat{\mathbf{b}}_l\right|$
- $F_2^w(r_\perp, r_\parallel) = \left\langle \left|\mathbf{w}(\mathbf{r}_1) - \mathbf{w}(\mathbf{r}_2)\right|^2 \right\rangle$,
  $F_2^B(r_\perp, r_\parallel) = \left\langle \left|\mathbf{B}(\mathbf{r}_1) - \mathbf{B}(\mathbf{r}_2)\right|^2 \right\rangle$





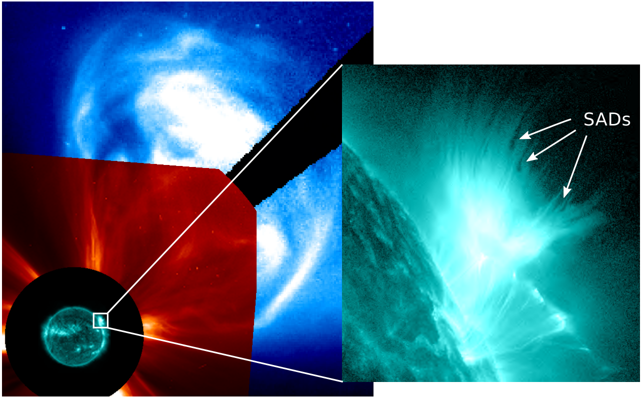


Plasmoid Instability, Summary

- Plasmoid Instability in 2D can facilitate fast, nearly S-independent reconnection even in resistive MHD, and can trigger even faster Hall reconnection if current sheet fragment becomes thinner than d_i
- However, plasmoid-instability mediated reconnection in 3D is qualitatively very different from that in 2D. Interestingly, in fully developed state, reconnection rate in 2D and 3D are comparable.
- Interaction between oblique tearing modes can lead to self-generated turbulent reconnection
    - Energy fluctuations preferentially align with the local magnetic field, which is one of the characteristics of MHD turbulence
    - The spectra of magnetic energy and kinetic energy fluctuations both satisfy power laws.
    - The turbulence is highly inhomogeneous, due to the presence of magnetic shear and outflow jets, therefore traditional turbulence theory may not be applicable.

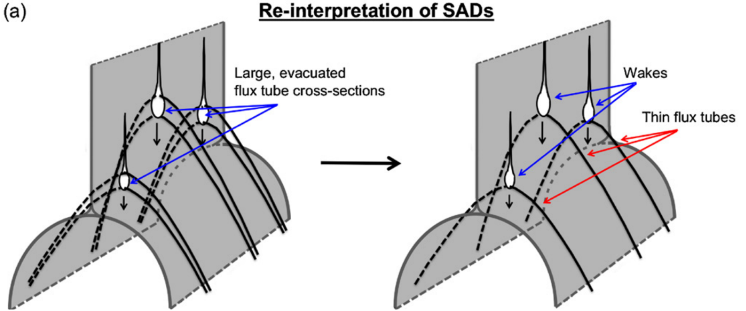
Observation of Supra-Arcade Downflows (SADs)

- First reported in McKenzie & Hudson APJ 1999
- Low emission, low density ($< 10^9 cm^{-3}$), high temperature ($\sim 10^7$), wavy structures surrounded by bright fan above flare arcade
- Average lifetime 10-20 min



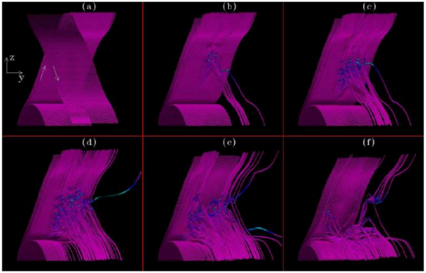
Interpretations of SADs

- Old interpretation – SADs are cross sections of reconnected flux tubes from "patchy" reconnection
- New interpretation – SADs are wakes behind cross sections of reconnected flux tubes
- Difficulty – Why wakes are not filled in by surrounding high density plasmas?

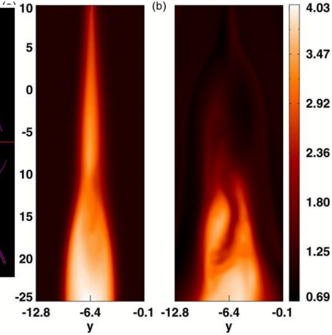


Savage et al. APJ 2012

Some Existing simulations of SADs



Linton et al. 2009

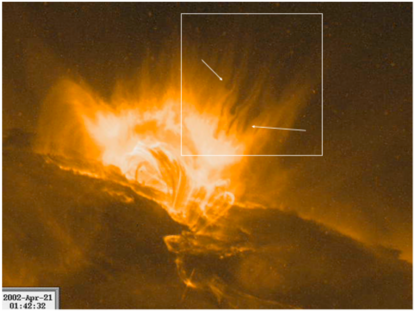


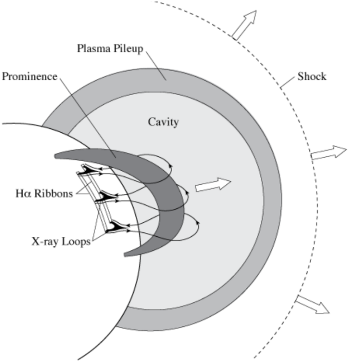
Cassak et al. 2013

- Linton et al. employed anomalous resistivity localized in both space & time
- Cassak et al. argued density gradient is important. Reconnection is continuous in time so SADs are not filled in, but must be patchy along the out-of-plane direction.

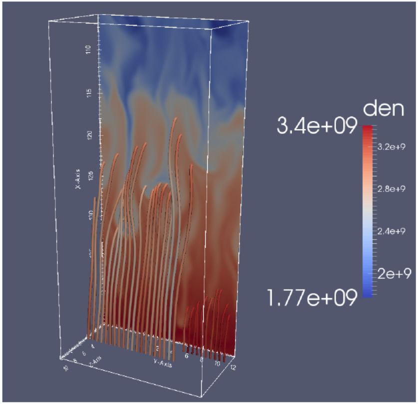
Can Rayleigh-Taylor Type Instabilities be the Cause of SADs?

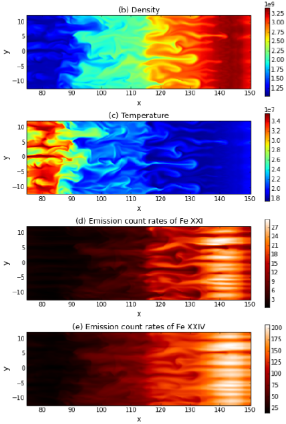
- SADs occurs predominantly with $\mathbf{k} \cdot \mathbf{B} \simeq 0$ — interchange/ballooning modes
- High pressure below the arcades — bad curvature
- Low density outflow jet pushes against high density arcade region





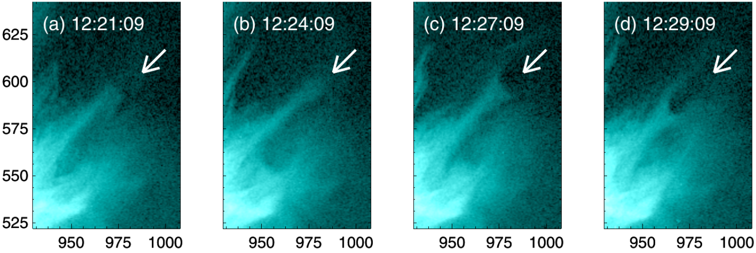
3D Simulation with Harris Sheet

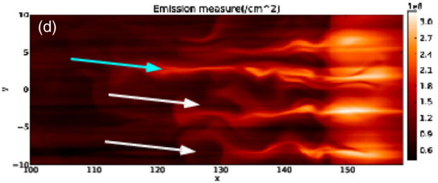




Guo et al. APJL 2014

New R-T “Mushrooms” at the Tips of Spikes





Innes et al. APJ 2014

Conclusion — SAD-like structures can arise in the exhaust region of reconnection as a consequence of R-T type instabilities, without reconnection itself being localized in either space or time.

What's Next

- Turbulent Reconnection in 3D
  - Highly inhomogeneous, due to the presence of magnetic shear and outflow jets — Need new theory or phenomenology
  - Self-generated vs. externally driven turbulent reconnection
  - Current sheet broadening due to self-generated turbulence — Sufficient to explain solar observation?
  - Include Hall effect
- Supra-Arcade Downflows
  - Include anisotropic thermal conductivity so that we can "see" arcades in synthetic emission
  - Line-tied boundary condition
  - High S simulations — current sheet spontaneous becomes patchy
- CME, plasmoids, and SADs in a single model
- Improve fluid models through closure schemes (e.g. recent work by Liang Wang & Ammar Hakim with higher moments)

Possible Connection with Lab. Plasma Physics

- Plasmoid instability in sawtooth crash — with Sybille Günter & coworkers in cylindrical geometry; maybe possible in 3D toroidal geometry?
- Explore new regimes in the phase diagram with FLARE or high energy density laser plasmas experiment (Hanto Ji, Will Fox, et al.)
- Plasmoids in NSTX experiment? (Nimrod simulation by Fatima Ebrahimi)
- Open to suggestions!